The formation epoch of massive ellipticals, as traced by radio galaxies

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Abstract. I review the current status of an on-going investigation into the stellar and dynamical ages of the oldest known galaxies at $z > 1$. The spectroscopic data, when compared with the predictions of a range of recent evolutionary synthesis models, continue to indicate that the oldest galaxies at $z \simeq 1.5$ are already > 3 Gyr old. Moreover, comparison with new models which incorporate chemical evolution, suggests that this result may be less sensitive to the assumed metallicity than was previously suspected. Such ages should therefore be taken seriously as constraints both on theories of galaxy formation and on cosmological models. Dynamically these objects also appear well evolved; they display de Vaucouleurs surface brightness profiles, and I demonstrate that their HST-derived morphological parameters place them on the same Kormendy relation as the $z \simeq 1$ 3CR galaxies. Finally I consider the ages of these intermediate redshift objects in the context of our recently completed SCUBA sub-mm survey of radio galaxies spanning the redshift range $z = 1 \rightarrow 4$. These data indicate that the main epoch of star-formation in radio galaxies lies at $z \simeq 4$, a result which fits naturally with the ages of the oldest galaxies at $z = 1.5$ within an open Universe.

1. Introduction

Even a very low-level burst of star-formation activity can easily obscure the true colours of the dynamically-dominant stellar population in a high-redshift galaxy. For this reason it is necessary to use the reddest (unreddened) galaxies at a given redshift to set meaningful constraints on their primary formation epoch. As demonstrated by Dunlop et al. (1996), Spinrad et al. (1997) and Dunlop (1999) the reddest ($R - K \simeq 6$) optical identifications of milli-Jansky radio sources have provided the best examples discovered to date of passively evolving galaxies at redshifts $z > 1$. As discussed by Dunlop (1999) there can be little doubt that the red colours of 53W091 ($R - K = 5.8$; $z = 1.55$) and 53W069 ($R - K = 6.3$; $z = 1.43$) are due to evolved stellar populations rather than dust. However, the initial attempt at accurate age-dating of 53W091 by Dunlop et al. (1996) has since stimulated considerable debate and controversy (Bruzual & Magris 1997, Yi et al. 1999, Heap et al. 1998).

In the next section I summarize the *uncontroversial* facts about these objects. I then consider the controversy over their precise ages and, focussing

on 53W069, demonstrate that there is in fact rather *little disgreement* between the ages inferred from different evolutionary synthesis models, provided fitting is confined to the high-quality rest-frame near-UV spectra. Following this I revisit the issue of age-metallicity degeneracy before moving on to consider the morphologies of these galaxies, and their ages in the context of our recently completed major SCUBA survey of dust-enshrouded star-formation in high-redshift radio galaxies.

2. 53W091 and 53W069: uncontroversial facts

The Keck spectra of 53W091 (Dunlop et al. 1996; Spinrad et al. 1997) and 53W069 (Dunlop 1999; Dey et al. in preparation) both display strong spectral breaks at rest-frame wavelengths of 2640Å and 2900Å (along with several other repeatable absorption features) which prove beyond doubt that their ultraviolet spectra are dominated by starlight from F stars. This is illustrated in Figure 1; the near-ultraviolet SED of 53W091 is essentially indistinguishable from an F5V star, while that of 53W069 is best described by an even redder F9V star. Since for ages less than $\simeq 5$ Gyr essentially all spectral synthesis models predict that the *near-ultraviolet* light of a stellar population should be dominated by main-sequence stars, this means that the main-sequence turnoff point in these stellar populations must have evolved into the mid F-star regime.

Figure 1 also shows that 53W069 appears to be a cleaner example of a genuinely coeval stellar population; the SED of 53W091 can be constructed by adding a low-level population of F0V stars (or some other comparably blue low-level component) to the SED of 53W069. Deriving the ages of these objects thus boils down to 'simply' determining how long it takes for the near-ultraviolet light from an evolving main sequence to impersonate the SED of an F9V star. It is worth noting that, at the time of writing, these two galaxies remain the only objects at redshifts as high as $z \simeq 1.5$ for which this type of potentially accurate age dating is possible.

3. Age controversy

3.1. Model dependence

Following the discovery of 53W091, Dunlop et al. (1996) derived an estimate for its age of 3.5±0.5 Gyr. This estimate was based primarily on comparison with a main-sequence only model of spectral evolution, with special emphasis placed on the (reddening independent) strength of the the 2640Å and 2900Å spectral breaks. The age-dating of this galaxy was then explored in more detail by Spinrad et al. (1997) who highlighted the disagreement between different models (especially if $R-K$ colour was included as a fitted quantity), but again concluded that an age of 3.5 Gyr appeared to be the most reasonable estimate of the time elapsed since cessation of star-formation activity. Subsequently, however, both Bruzual & Magris (1997) and Yi et al. (1999) have concluded in favour of an age as young as 1.5 Gyr.

However, it transpires that a significant fraction of this disagreement arises from the fact that Bruzual & Magris (1997) and Yi et al. (1999) have included

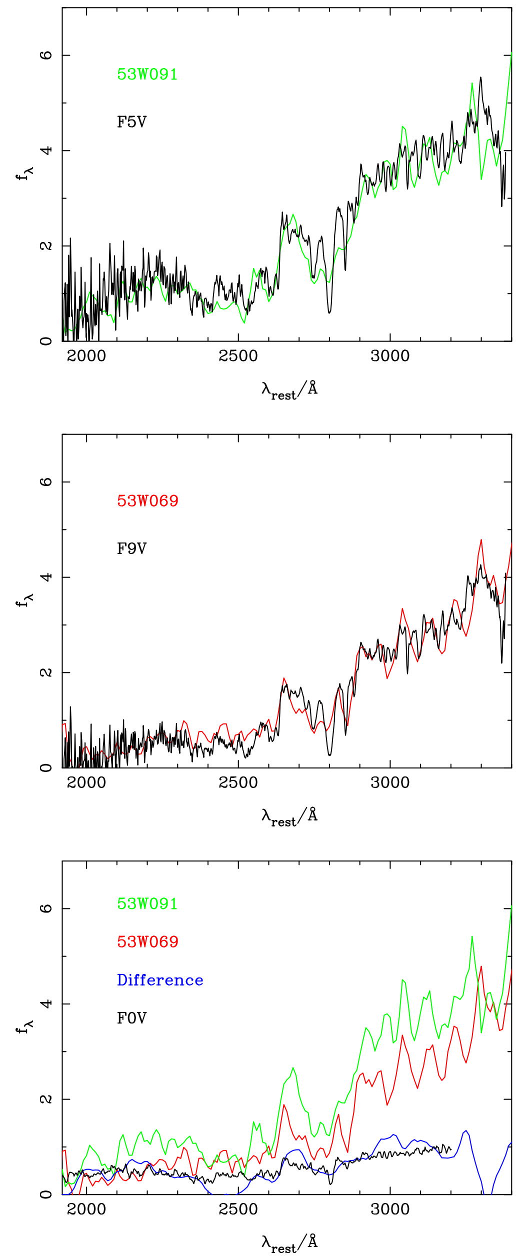

Figure 1. Top Panel: Galaxy rest-frame Keck spectrum of 53W091 compared with an average F5V IUE spectrum. Middle Panel: Galaxy rest-frame Keck spectrum of 53W069 compared with an average F9V IUE spectrum. Bottom Panel: Comparison of the properly scaled rest-frame UV spectra of 53W091 and 53W069 with a smoothed version of the difference spectrum compared with an average F0V IUE spectrum.

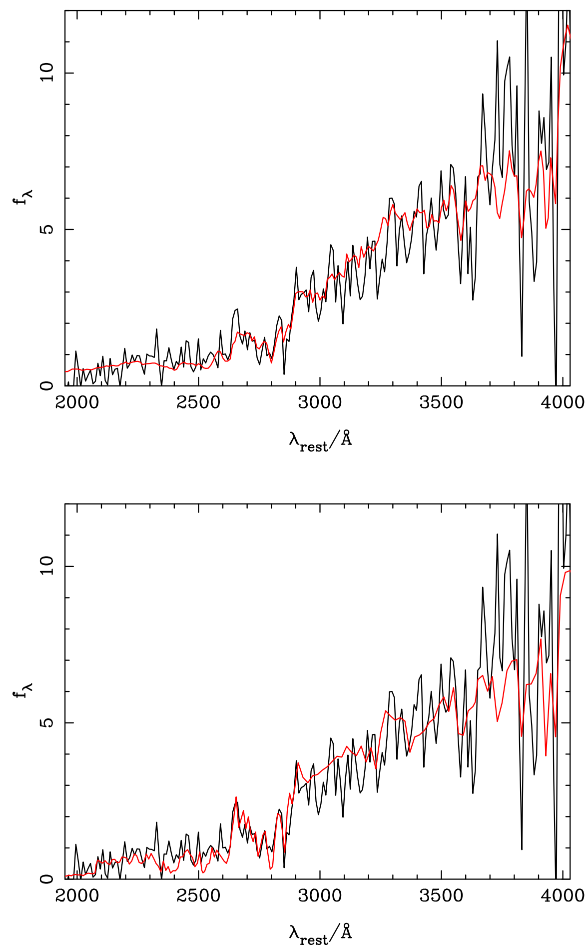

Figure 2. Upper panel: The spectrum of 53W069 overlaid with the best fitting Bruzual-Charlot model, which has an age of 3.25 Gyr. Lower panel: The spectrum of 53W069 overlaid with the best fitting model from Jimenez et al. (1999), which has an age of 4.25 Gyr.

$R-K$ colour as an important factor in the fitting process. This dilutes much of the advantage offered by the detailed rest-frame near-ultraviolet Keck spectra obtained for these objects, because the evolution of $R-K$ colour at such redshifts depends not only on the main-sequence, but also on modelling of the later stages of stellar evolution, over which there remains much more controversy (due to complications such as mass loss; see Jimenez et al. 1999). In fact, if fitting is confined to the Keck spectrum, the models of Bruzual and of Yi indicate an age of $\simeq$2.5 Gyr, while the most recent models of Jimenez indicate an age of 3.0 Gyr. Given the uncertainties, these ages are basically consistent, albeit 0.5 - 1 Gyr younger than the original age quoted by Dunlop et al. (1996) (although the spectral breaks, especially the 2900Å break continue to favour an older age $\simeq 4$ Gyr - see Dunlop 1999).

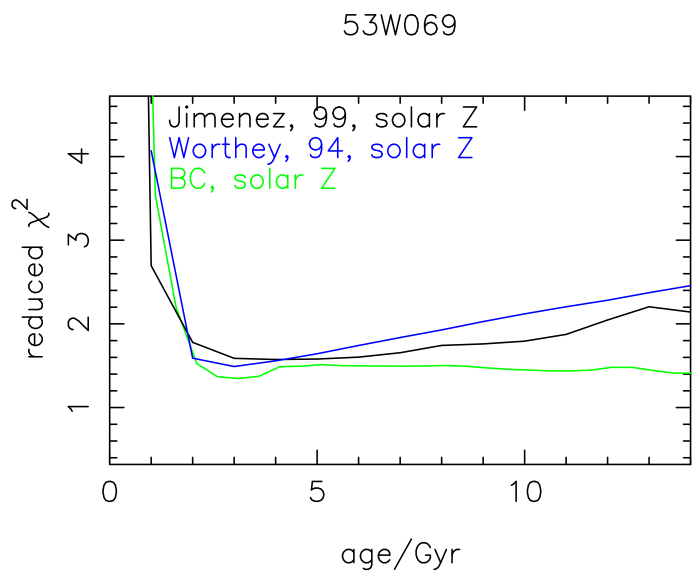

Figure 3. Reduced chi-squared versus the inferred age of 53W069 derived from attempting to fit the Keck spectrum of 53W069 with the evolutionary synthesis models of Jimenez et al. (1999), Bruzual & Charlot (1993) and Worthey (1994).

However, as explained above, 53W069 provides a better example of a clean coeval stellar population, and for this galaxy it appears that essentially all existing models indicate an age > 3 Gyr. Figure 2 shows the data fitted by the updated models of Bruzual & Charlot (1993) (inferred age 3.25 Gyr) and by the most recent models of Jimenez et al. (1999) (inferred age 4.25 Gyr).

3.2. Age constraints for 53W069

Figure 3 shows a plot of reduced chi-squared versus inferred age, derived from attempting to fit the models of Jimenez et al. (1999), Bruzual & Charlot, and Worthey (1994) to the Keck spectrum of 53W069. The models of Jimenez favour an age about 1 Gyr older than the models of Bruzual & Charlot, but it is clear from this plot that this disagreement is not very dramatic in terms of quality of fit. The key point is that all the models favour an age of 3 Gyr or greater, with ages younger than 2.5 Gyr formally excluded. It is important to re-stress that these ages are based on instantaneous starburst models, and thus indicate the time elapsed since cessation of major star-formation activity with no additional time included for the process of galaxy/star formation. However, they do assume solar metallicity.

3.3. Impact of varying metallicity

A major concern with this type of spectral age dating is that, as explored by for example Worthey (1994), deduced age is approximately inversely proportional to assumed metallicity for most spectral age indicators. For the 2640Å and 2900Å breaks this age/metallicity degeneracy appears to be not quite as severe as this (Dunlop et al. 1996; Fanelli et al. 1992), but nonetheless it is clear that the

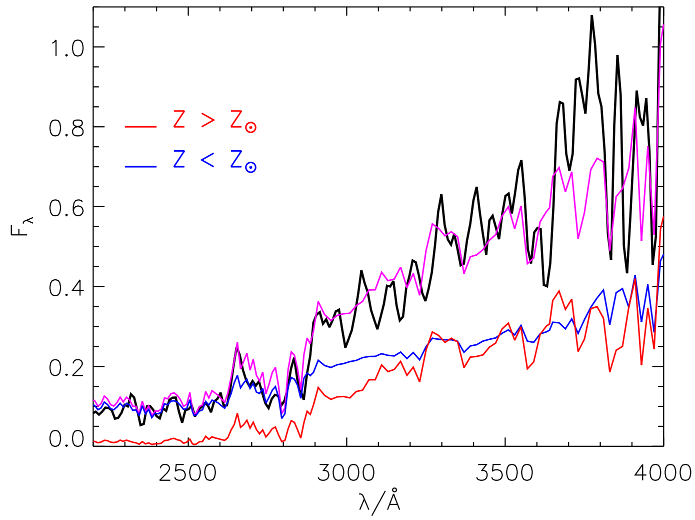

Figure 4. The Keck spectrum of 53W069 fitted with the composite metallicity model of Jimenez et al. (1999) at an age of 4 Gyr. The mass-averaged metallicity of this model is $\simeq 2 \times$ solar, but the figure also illustrates how the sub-solar metallicity stars continue to dominate the predicted SED shortward of 3500Å, leading to an age estimate which is unexpectedly robust to varying metallicity.

inferred ages of 53W091 and 53W069 can be reduced to less than 2 Gyr if one assumes the observed stellar population consists only of stars with twice solar metallicity.

However, new models of elliptical galaxy formation/evolution developed by Jimenez et al. (1999), and by Yi et al. (1999) suggest that adoption of this simple-minded age-metallicity degeneracy may lead to an overly pessimistic view of the accuracy to which ages can be derived. These models include chemical evolution during the initial starburst, in an attempt to produce a realistic stellar population of composite metallicity. The interesting consequence of comparing the predictions of such models to the near-ultraviolet SED of 53W069 is that the inferred age is essentially unchanged from that derived using the simple solar metallicity models, despite the fact that the mass-weighted metallicity can be as high as twice solar. The reason for this is illustrated in Figure 4 which shows the best fit obtained using the 2×-solar metallicity composite model of Jimenez et al. (1999b) to 53W069, at an age of 4 Gyr. The plot shows that while the high metallicity stars dominate the red end of the spectrum, sub-solar metallicity stars continue to dominate shortward of $\lambda \simeq 3300$Å, with the consequence that the derived age is more robust than would have been niavely expected. Indeed the statistical fit obtained with this 4 Gyr composite model is substantially better than that achieved with any single metallicity model.

This result, coupled with the rather good agreement between different models discussed above, suggests that an age limit of > 3 Gyr for the oldest galaxies (and hence the Universe) at $z = 1.5$ should be taken seriously. Such an age

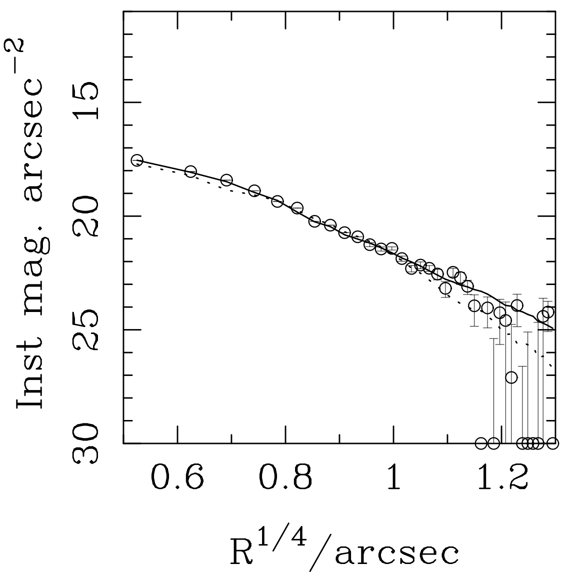

Figure 5. HST H-band profile of 53W069 (circles) compared with the best-fitting pure de Vaucouleurs law after convolution with the NICMOS H-band PSF (solid line) (Bunker et al. in preparation)

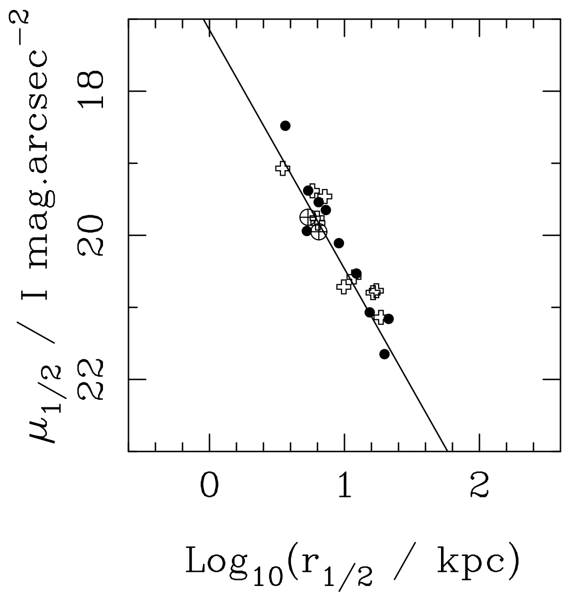

Figure 6. The Kormendy relation displayed by 3CR radio galaxies at $z = 0.2$ (solid circles) overlaid with the (indistinguishable) relation displayed by 3CR galaxies at $z = 0.9$ (crosses) after allowing for 0.6 magnitudes of passive evolution in the I-band. The solid line shows the best fitting Kormendy relation which has a slope of 3.2. The locations of 53W091 and 53W069 on this diagram are indicated by the large circle+cross symbols. They lie on the same Kormendy relation, but with scalelengths a factor $\simeq 3$ smaller than the mean scalelength displayed by the more radio-powerful 3CR galaxies.

is also consistent with the collapse epoch of these objects as inferred from the power-spectrum analysis of Peacock et al. (1998).

4. Morphology and size

HST I-band and J-band images of 53W091 and 53W069 indicate that both galaxies are dominated by a bulge component both above and below the 4000Å break (Waddington et al. in preparation). The most powerful evidence that morpholically these galaxies are dynamically evolved ellipticals comes from analysis of the deep NICMOS H-band image of 53W091 obtained by Bunker et al. (in preparation). In Figure 5 I show the luminosity profile derived from this image; a simple de Vaucouleurs law with no nuclear component provides a significantly better fit to the data than a disc with a nuclear contribution, and the derived scalelength is $r_e = 3.5$ kpc ($\Omega_0 = 1$, $H_0 = 50$km s^{-1} Mpc^{-1}).

The derived scalelengths and surface brightnesses of both 53W091 and 53W069 are placed in context in Figure 6, which demonstrates that they lie on the Kormendy relation described by 3CR radio galaxies (at both high and low redshift; McLure & Dunlop 1999), towards the lower end of the scalelength distribution of these more powerful radio galaxies. As pointed out by McLure & Dunlop (1999), a reanalysis of the available HST data on 3CR galaxies provides no evidence for any significant dynamical evolution of massive ellipticals between $z = 1$; the location of 53W091 and 53W069 on Figure 6 is not unexpected given their moderate radio power (see McLure et al. 1999), and suggests that the Kormendy relation for massive ellipticals may already be in place by $z \simeq 1.5$.

5. Formation epoch inferred from sub-millimetre observations

It is interesting to attempt to relate the dynamical and spectral passivity displayed by 53W091 and 53W069 at $z \simeq 1.5$ to direct attempts to determine the main epoch of radio galaxy formation (and possibly all spheroid formation). There is certainly some evidence that, dynamically, radio galaxies are different at $z > 3$ than at lower redshifts (van Breugel et al 1998), but the complications of radio activity have made it difficult to constrain the major epoch of star-formation activity in these objects from optical/near-infrared observations.

However, my collaborators and I have recently completed the first major SCUBA sub-mm survey of dust-enshrouded star-formation activity in radio galaxies between $z = 1$ and $z = 4$, the results of which indicate that the main epoch of star-formation activity in these objects lies at $z > 3$. Previous sub-mm detections of high-redshift radio galaxies have been at $z \simeq 4$ (Dunlop et al. 1994; Hughes et al. 1997; Ivision et al. 1998) but the extreme radio powers of the detected objects made it impossible to tell whether their inferred large dust and gas masses were primarily due to cosmic epoch, or instead related to extreme radio power. Now, as illustrated in Figure 7a, we have achieved sufficient coverage of the $P - z$ plane to separate these effects, and by considering a slice at constant radio power, can for the first time derive the redshift dependence of sub-mm emission in powerful radio galaxies. As shown in Figure 7b, the average sub-mm luminosity (and hence inferred gas mass and star-formation rate) rises out to at least $z \simeq 4$ with sub-mm luminosity growing approximately propor-

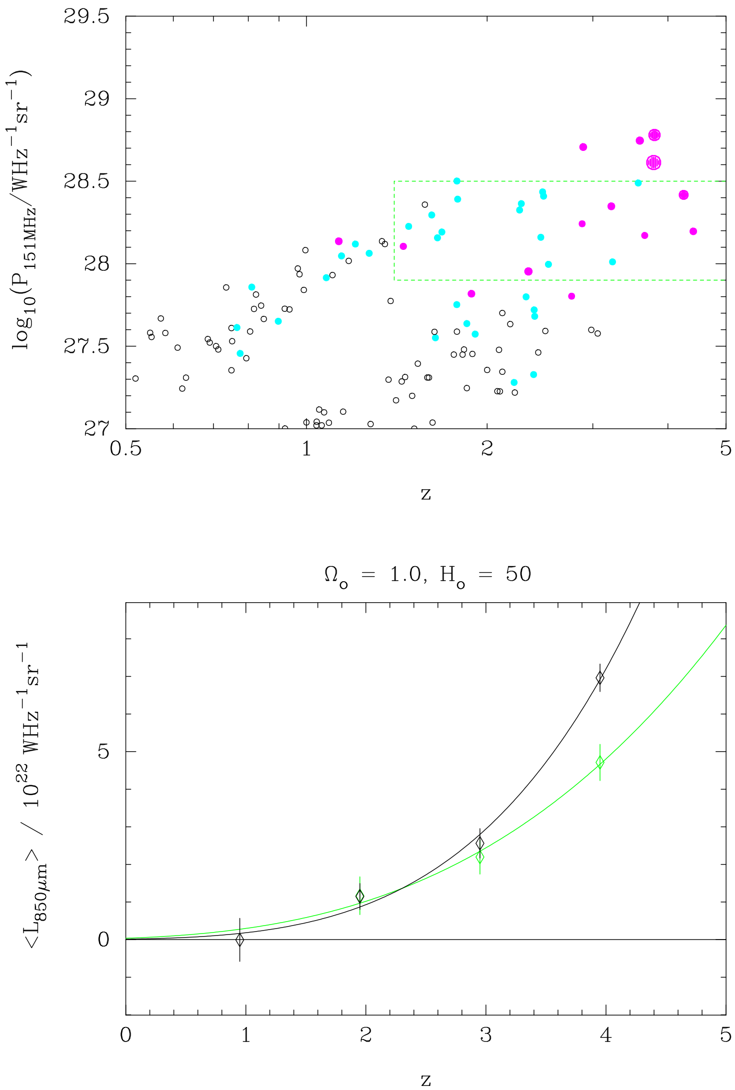

Figure 7. Upper panel: The radio-luminosity redshift plane showing the location of the $\simeq 50$ radio galaxies observed with SCUBA by Archibald et al. (in preparation). Red symbols of increasing size indicate detections of increasing brightness at $850\mu m$. Blue symbols indicate non-detections. The green box defines a subsample of objects which span the redshift range $z = 1 \rightarrow 4$ at constant radio luminosity, allowing separation of the normally correlated effects of redshift and luminosity. Lower panel: Weighted mean $L_{850\mu m}$ for the radio galaxies observed with SCUBA in redshift bins centred on $z = 1, 2, 3, 4$. The black diamonds refer to all the radio galaxies observed, while the green diamonds refer only to the subset of radio galaxies lying within the constant radio luminosity strip indicated in the upper panel. The lines are fits to the data of the form $L \propto (1+z)^{\alpha}$ to indicate the strength of the evolutionary trend. For all galaxies observed $\alpha \simeq 4$, while for those in the constant luminosity strip $\alpha \simeq 3$. Such evolution is of very similar strength to that deduced for many other populations of extragalactic objects out to $z \simeq 2.5$ (Dunlop 1998), but here appears to continue out to at least $z \simeq 4$.

tional to $(1+z)^3$. This strongly suggests that the bulk of star-formation in radio galaxies occurred at redshifts $z \simeq 4$ or higher, and that star-formation in radio galaxies, and arguably ellipticals in general, is close to completion by $z \simeq 3$.

Finally, I note that, in a collaboration led by Rob Ivison, we have recently obtained a deep (10-hour) SCUBA image of the field centred on the z = 3.8 radio galaxy 4C41.17. This new image reaches an rms sensitivity of $\simeq 1$ mJy at $850\mu m$ (Ivison et al. in preparation), and 4C41.17 itself is clearly detected in the centre, confirming the early single-element UKT14 detection by Dunlop et al. (1994). However, the surprising thing about this image is that, despite the fact that 4C41.17 is one of the most luminous sub-mm sources ever detected, it is *not* the most luminous source in this 2.8-arcmin diameter image. A more luminous, apparently resolved $\simeq$ 12mJy source lies to the south of the radio galaxy at a projected distance of $\simeq$ 200 kpc, assuming it lies at the same redshift (an assumption supported by its sub-mm colours; Ivison et al. in preparation), and a third moderately bright source lies to the north.

Taken together these sources indicate a considerable excess of dust enshrouded star formation in the vicinity of this high-redshift radio galaxy compared with that found in blank field surveys (e.g. Hughes et al. 1998, Eales et al. 1998). Although this is only a single field, it is strongly suggestive of violent dust-enshrouded star formation in a high-redshift proto-cluster for which the radio galaxy has acted as a signpost. Such images provide at least circumstantial support for the idea that the cosmological evolution of dust mass and SF activity plotted in Figure 7b might apply not just to radio galaxies but to spheroids in general, especially those born in rich environments (see also Renzini 1999).

6. Conclusion

Radio galaxies are obviously a special subset of all ellipticals, and very red/passive galaxies such as 53W091 and 53W069 form a special subset of radio galaxies. However, this does not necessarily mean they are unrepresentative of ellipticals in general. Rather, it may simply mean that it is rare to find elliptical galaxies at $z > 1$ which have undergone so little star-formation activity over the $\simeq 3$ Gyrs prior to observation. As pointed out by Jimenez et al. (1999c), most realistic models of elliptical formation involve sufficient low-level secondary bursts of star-formation to frequently mask the true optical-infrared colours of a dynamically dominant stellar population at $z > 1$ (cf Zepf 1997).

The apparent lack of significant dynamical growth of radio galaxies since $z \simeq 1$ discussed above (McLure & Dunlop 1999) may also be representative of massive ellipticals in general. Certainly there is now a growing body of observational evidence from infrared studies that cluster ellipticals (de Propris et al. 1999) and field ellipticals (Dunlop et al. 1999) are essentially all in place by $z \simeq 1$ (cf Kauffman & Charlot 1998).

This lack of dynamical action since $z \simeq 1$, and the ages of the oldest ellipticals at $z > 1$, both favour a universe with $\Omega_{matter} < 1$.

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